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Beyond land cover change: Towards a new generation of Land System Models

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Highlights:

- Lack of new land use or land system modelling concepts published in recent year
- Land system models are frequently insufficiently evaluated
- Advances are to better represent human agency in land system models are identified
- Large potential identified for land system models to contribute to the identification and design of sustainability solutions

Abstract

Land system models play an important role in exploring future land change dynamics and are instrumental to support the integration of knowledge in land system science. However, unsatisfactory progress has been made in achieving these aims due to insufficient model evaluation and limited representation of the underlying socio-ecological processes and human agency. We discuss how land system models can better represent multi-scalar dynamics, human agency and demand-supply relations, as well as how to achieve deeper insights from model evaluation. By addressing these issues we outline pathways towards a new generation of land system models that allow not only the assessment of future land cover pattern changes, but also enable societal envisioning in supporting the design of sustainability solutions.

Keywords: Land use, Land cover, Simulations, Integrated Assessment, Agent-based models, Sustainability

Introduction

As with other emerging scientific fields, rapid advances in land use modelling were made during the first decades of the development of land system science. Several alternative paradigms for modelling land use change processes were developed [1]. Over the past decade, the number of publications related to land use change modelling has continued to increase. Publications in this period indicate three trends: 1) The frequent application of easily available land use models in case-studies aimed at informing spatial planning. Many of these studies apply relatively simple spatial models, e.g. using a combination of Markov chains for the quantity of change and cellular automata to emulate patterns of land cover change [2]; 2) The incremental improvement of existing models and modelling concepts [3-5]; 3) The development of agent-based models for specific case-studies that are difficult to generalize beyond the specific context, characterized by O'Sullivan et al. [6] as the YAAWN syndrome ("Yet Another Agent-Based Model … Whatever … Nevermind …").

These trends illustrate the relevance of land change modelling as a tool in land system science. However, the limited amount of novel modelling concepts put forward raises the question of whether current tools and modelling concepts allows the full potential of land system science to be reached?

This question cannot be answered in a generic manner. In many projects existing land use models have successfully played a role in synthesizing project results [7,8] or in structuring discussions with stakeholders [9,10]. In spite of this, there is a recurring notion in the literature of the model being presented as the endpoint, rather than as a process of learning from the model design or application. This is unfortunate since modelling systems are rarely adopted by stakeholders after the lifetime of a project [11].

The application of currently available models for policy and planning is hampered by uncertainty throughout the modelling process, and limited progress has been reported in understanding or reducing this uncertainty. While predictive accuracy is just one metric of a model's value, earlier validation efforts showed that few land use models outperformed a simple 'no change' model [12]. More recently, Mas et al. [13] showed that for a similar (virtual) landscape four different, frequently used, land change models resulted in strongly different outcomes. A comparison of global land use models and integrated assessment models (IAMs) showed that, in essence, the differences between the models analyzed were greater than the differences between the different scenarios modelled [14,15]. A review of calibration and validation practices in land use models [16] found that 31% of the applications did not report any model evaluation, while the rest were predominantly assessed in terms of their location accuracy, ignoring the uncertainty in the quantity and spatial patterns of land use. Only 17% of the model applications reported an uncertainty analysis, and 12% reported a sensitivity analysis.

Given these conditions, the objective of this paper is to identify opportunities to improve land use modelling towards a new generation of land system models that is better able to synthesize and formalize insights, make sources of uncertainty in projections transparent, and support the design of sustainability solutions.

Key dimensions for land system modelling

Addressing the multi-scalar challenge

The dilemma of choosing an appropriate scale for modelling is well-known for land system science and multi-scalar dynamics have been a challenge since the origin of the research field [20-22]. Global drivers affect places in different ways and aggregate impacts of local responses feedback to the global system. Coupling of models operating at different scales has been proposed to address the multiple levels of analysis needed to describe all important processes [23-26]. However, usually only a one-way, top-down flow of data occurs, as incorporating feedbacks would lead to computationally complex iterations between models. Moreover, different modelling concepts and behavioral assumptions at different levels may lead to inconsistencies between models at different scales ("ugly constructs" according to Voinov and Shugart [27]).

Addressing the multi-scalar challenge requires new model structures that are truly multi-scale, and thus likely more complex than current models. Experiences in other fields of science may be instrumental to inform such a design, i.e. the multi-level structure employed in remote sensing [27a] or multi-scale modelling in physics [27b]. In physics sometimes a sequential modelling is used in which micro-models pre-compute details of some of the constitutive relations in the macro-model. Such an approach may also be used in land system science. In addition, rather than simulating all underlying processes, a larger role may be given to meta-studies, synthesizing empirically measured responses in local studies to inform model design [28]. Such micro-level models or meta-studies should aim to synthesize the role of contextual conditions on responses, which can be translated into simple model rules implemented within a higher level model to account for the local level responses.

When feedbacks between micro and macro levels are important, concurrent multi-scale modelling (also referred to as nested modelling) may be applied in which quantities needed in the macro-scale model are computed on-the-fly from micro-scale models as the computation proceeds. Concurrent coupling allows one to evaluate these forces at the locations where they are needed to resolve local behavior and then use macro-models elsewhere.

Conversely, new models could focus on different model structures that better reflect the important scalar dynamics more explicitly. For example, models of global trade flows of food commodities use a different approach than models of decision making about land use at local levels. However, combining models of trade flows with sub-national models of human agency would create new modelling approaches of considerable utility. An example of such a modelling approach is provided by Lamperti et al. [30] who provide an alternative, agent-based, model structure to the classic coupling of general equilibrium models and climate models in IAMs.

A confounding factor in the multi-scalar challenge is the wide variety of telecoupled processes and the impact of location conditions on land change outcomes [31,32]. The location of agricultural expansion will affect production and impacts on biodiversity. Extent and spatial patterns of expansion will differ between locations as a result of the local socio-economic, cultural and demographic context. While downscaling of global model outcomes to pixels is well established and an integral part of IAMs, feedbacks from the local to the global-level are poorly captured with this approach. Global land use models are, therefore, often unable to appropriately capture processes such as displacement effects, multi-level governance of land use, adaptive learning, not fully economically driven decision making and human behavior that underpins decision making [32]. Part of such bottom-up processes could be captured by nesting micro-models within the macro-models to capture bottom-up responses in a more adequate manner as has been described above. However, when these responses are moderated through processes at different scales capturing the bottom-up response may not be sufficient. Displacement and other spill-over effects can occur through multiple mechanisms [55][32a] and the spatial scale across which these effects occur depends on the actors and processes involved, such as the structure of the value chain and markets, which can cause spillovers to occur from within the same landscape to across world regions. Economic models (i.e. equilibrium models) that can address such displacement processes have fixed representations of modelling units and can only address displacement effects between these units. While qualitative methods and conceptual models are able to describe such cross-scale mechanisms, the consistent representation in models is still challenging.

Resilience of the land system has received increased attention given the interconnectedness of the global system and the potential consequences from shocks, such as extreme weather events or trade conflicts. Land system models have potential to simulate such shocks and the resulting consequence so that the systems behaviors can be better understood and negative outcomes mitigated. However, to date such modelling remains lacking, in part due to the challenges in consider cross scale interaction in dynamic (i.e. non-equilibrium) conditions.

The next generation of land use change models should give more attention to cross-scale processes rather than focusing on a single scale or level of modelling to better represent spillover processes that are increasingly important in globalized land use. To achieve this we may have to move away from using simple spatial (i.e. world regions or pixels) or organizational entities (individual or institutional agents) as units of simulation to more blended approaches where the processes of interaction are central to the simulation rather than the units affected by these processes.

Embrace complexity and diversity of human agency

The attractiveness of agent-based modelling for land use change originates from the explicit representation of the diversity in decision making and the desire to incorporate agent-interactions [33,34]. However, most agent-based modelling is focused on the local scale because finding sufficient empirical data about decision making processes and outcomes at larger scales is extremely difficult. Attempts to use agent-based models at larger scales often resort to simplifications of the variation in decision making by linking agent-types directly to land cover types. While there is general agreement that decision making dynamics in land use can vary strongly across the globe, there is little empirical basis or theoretical insight to help selecting from different approaches to represent decision-making in simulation models [35].

To fill this gap, Malek et al. (subm) conducted a meta-analysis of case-studies to identify where, and under what conditions, certain modes of land-use decision making are found. The occurrence of archetypical types of decision making, ranging from satisficing behavior to utility maximization, were related to contextual conditions, leading to a predictive model that indicates what mode of land use decision making can be expected in a particular context (Figure 1). In spite of the large generalization, this synthesis is a first step towards global land use models that represent the variation in decision making [32]. In addition to the spatial variations, land-use decision making often shows an evolution over time [36], as is represented in models that incorporate adaptive behavior [37]. Moving away from the assumption of uniform and static decision making is a big step for large-scale land use models and does not necessarily mean that all should become agent-based modelling and represent individual agents. Differences in decision making mechanisms can also be reflected in spatial models that use pixels as units of simulation, either through the choice of determinants of location suitabilities or through the spatial extent accounted for in choosing the most optimal location for a particular land use. In large-scale global economic and integrated assessment models there have been several calls to represent heterogeneity and some early approaches have been proposed, however not yet related to land use [37a][37b].

A limitation of most agent-based modelling in land use studies is the focus on primary actors of land use change, mostly farmers. Recent developments show an increasing influence on land use decisions of distant land owners, investors and companies through large-scale land acquisitions, contract farming and investments [38,39]. To better account for such developments, insight into the decision making of these actors needs to be obtained. There are yet few studies [39a][39b] that explicitly account for this type of land change dynamics as most existing models are more tailored towards representing small-holder farmer decisions.

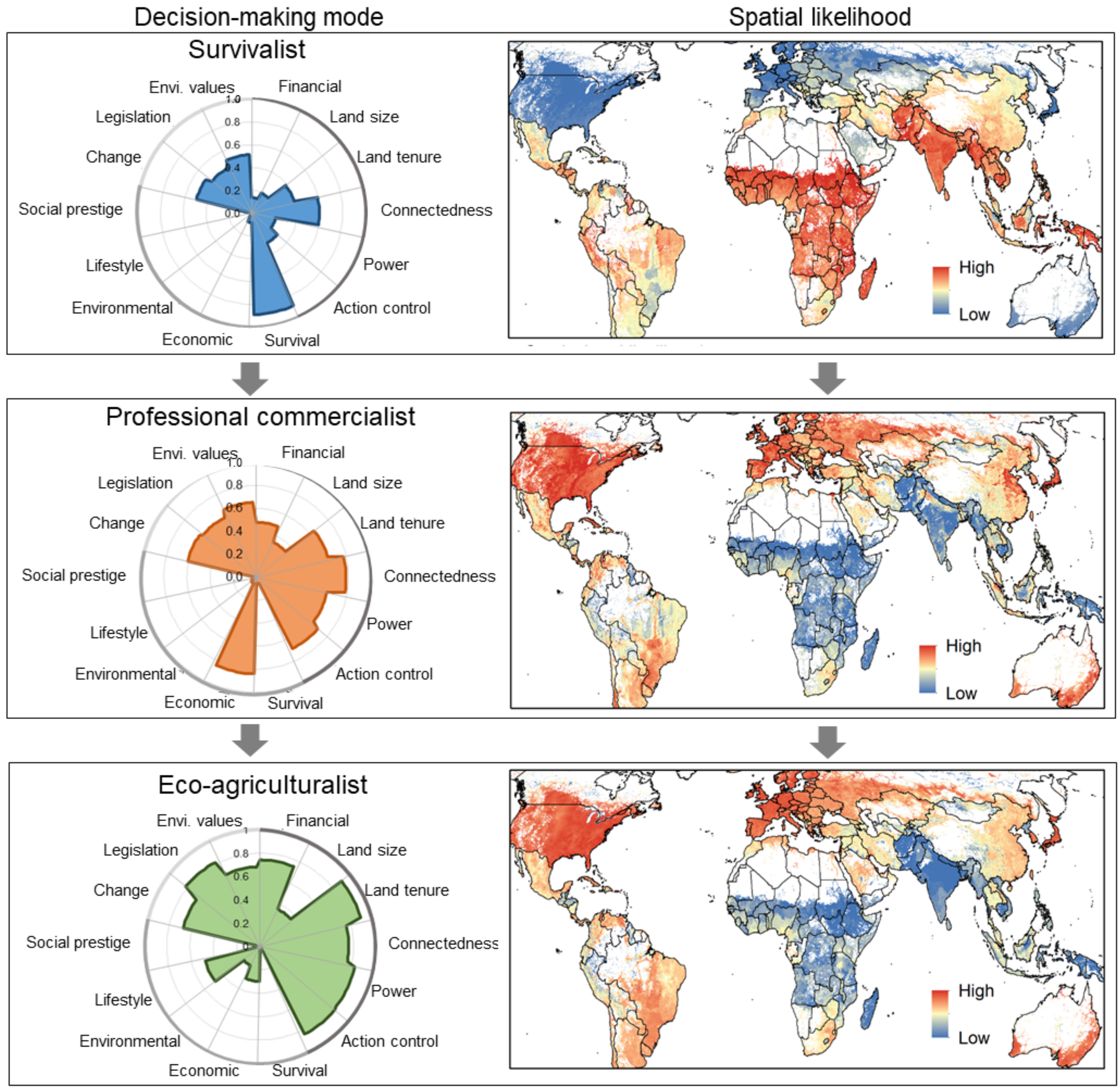

Figure 1: *Results of a meta-analysis of case studies reporting decision-making modes worldwide. Left: Radar charts showing average scores on abilities (financial, land size, land tenure, connectedness, power), objectives (survival, economic, environmental, lifestyle, social prestige) and attitudes (change, legislation, environmental values) for the different decision-modes; Right: Maps depicting likelihood of finding a specific decision mode based on extrapolation with socio-economic and biophysical context variables (Malek et al. subm).*

<u>Linking demand and supply</u>

While land system science is based on the notion of socio-ecological systems, we often still model only a symptom of the socio-ecological system dynamics: the conversion of one land cover to another. This is a direct result of the dependence on remote sensing data that reflect land cover. Only few models account for the, historically, most important pathway of fulfilling increasing demands for land-based commodities: land use intensification [36,40,41]. Instead, most models assume an external pressure or demand to steer land cover change quantities or use Markov chains to extrapolate from historic trends. The processes underlying this demand are not modelled explicitly and feedbacks between demand and supply are ignored. As an exception, general economic equilibrium models determine demand and supply across the full economy, where the costs of production can affect consumption patterns through price signals [42] and an economic choice is made between expansion of land area or intensification. Such analysis is useful, but lacks a representation of the spatial heterogeneity, as the spatial resolution of these models is often restricted to world regions. Additionally, other feedbacks in the system, including lifestyles, land tenure, advertising, markets and governance, can only be incorporated in stylized forms, e.g., through demand elasticities and production costs. Consumption of agricultural commodities, but also the use of other land-based commodities such as biofuels, are strongly determined by large corporations that impact consumption choices through markets and price incentives. Governments impact relationships between demand and supply, e.g., through trade barriers and subsidies for production or export of products [43]. As a result, consumer prices do not reflect the real production costs and consumer choices are often not economically rational, let alone fully accounting for health or environmental costs and benefits. While it is generally acknowledged that consumption choices are a strong determinant of land system change and offer a large potential to reduce pressures on land resources and environmental impact [44-46], there is relatively limited attention to this in land use modelling. The links and feedbacks between consumer and producer choices need to be represented in modelling to avoid a sole focus on production side solutions. Transformative change towards sustainability requires also addressing the fundamental drivers and behavioral choices in socio-ecological systems that that are the underlying causes of land system changes. While there is a rich literature on consumption behavior and an emerging knowledge on the role of supply chains [46a] these are hardly captured in land system models to allow a more quantitative exploration of the different pathways to fulfilling the demand for land-based products more sustainably.

Learning from modelling

Land use modelling is too often presented as a goal in itself, or for the purpose of 'prediction'. However, the model building and testing process is most useful in advancing our understanding of land use systems. This is evident in the rapidly growing field of participatory modelling, which aims at engaging the knowledge of stakeholders to create formalized and shared representations of reality and using models as boundary objects to collectively reason about environmental problems and foster two-way learning [Jordan et al. 2018][Gray et al 2018]. A review of 180 environmental sciences papers using participatory modelling identified a gap between the qualitative and quantitative development phases that hampers the use of participatory approaches to develop the more quantitative models for scenario analysis (Voinov et al. ??). However, final results are typically not the most valuable or convincing aspects of a modelling effort for policy makers and other stakeholders, but rather the rationale of the (cascading) processes of impact of a certain intervention [9,47]. Rather than seeing the model as a black box, it is the internal logic leading to a specific outcome that needs to be uncovered to convince stakeholders of appropriate actions. Similarly, models are also an important learning tool for researchers. Models force us to formalize our understanding of land systems: select those processes that are important, quantify relations and bring different components together into a consistent whole. In that sense, models can be a boundary object (i.e., platform that spans disciplinary boundaries to enable contributions and interpretations from diverse perspectives) in socio-ecological systems analysis [48].

Comparing model outcomes against reality (i.e., model validation) is also an opportunity for improving our system understanding [49]. While model validation is rather common for local to regional scale models [16], most global land use models have still never been compared against data [50]. Until recently, global land cover products were of insufficient quality to enable full validation. Recent global, multi-temporal datasets offer new opportunities to validate global land change models [51]. Of course, validation based on land cover outcomes is not necessarily conclusive, because different land change processes may lead to the same patterns (equifinality) and calibration based on past conditions does not imply predictability of future conditions. However, model evaluation, which includes validation, as well as uncertainty analysis, model verification, sensitivity analysis, and benchmarking (comparison with other models), is an essential step in learning about the system and the range of applications the model is suited for.

Recent model comparisons [14,15] show that large differences in outputs exist between land use models, even though most of the compared models use a common modelling paradigm (*viz*. IAMs). As these models are used to inform large-scale governmental assessments, such as those of the IPCC and to a lesser extent IPBES, this uncertainty is concerning. In addition, land use results in these assessments are harmonized from only one of many possible land-use models [52], and then used by climate or ecosystem models to explore uncertainty [53] - an approach which may neglect key elements of uncertainty in the land use projections. Furthermore, separate scenarios have been assigned to different individual models or a small group of IAMs [54], carrying the risk that urgent policy decisions are based on information that hardly reflects the uncertainty embedded in the choice of model.

While large differences between different model types are a challenge from a predictive point of view, they provide an opportunity for learning from model comparisons. Models that can simultaneously implement multiple, alternative process representations provide a computational laboratory to explore the applicability of hypothesized land system processes across a range of conditions, and iteratively improve our understanding of the broader socio-ecological system. Model representations that balance specificity and generality are a tool for theory development and testing, particularly for middle-range theories [55]. This approach is exemplified by Magliocca et al. [56] who tested the validity of generic theory to explain land use changes across different contexts in a virtual laboratory setting.

To derive the greatest insights from models, results need to be repeatable by researchers outside of the groups where a model was developed. This requires comprehensive model descriptions and full scenario outputs to be published, as well as making model code available with complete sets of input data to allow re-running or adaptation of existing simulations

Moving beyond exploration: land use modelling for the envisioning and design of sustainable futures

The majority of land change models are used to project exploratory scenarios under assumed future conditions. While such scenario studies have proven useful in anticipating future land use outcomes under uncertain drivers, it is often difficult to link these to the policy, behavioral and management decisions needed to arrive at more beneficial outcomes. As most of the model structures are based on current processes and parameterized or calibrated on past or current conditions, these models are not suited to assess socio-ecological system developments that strongly deviate from past conditions, such as the impacts of de-growth [57] or large scale migration [58] on land use. At the same time, awareness is growing that meeting the sustainable development goals requires large societal transformations, including behavioral changes, technological shifts and institutional arrangements. Most models are only able to address the 'shallow leverage points' of sustainability transformations and lack the capacity to address 'deep leverage points' [58a]. Moreover, such sustainability transformations will come with significant tradeoffs that require far-reaching decisions and societal envisioning processes.

Land use models have the capability to support societal envisioning processes by sketching out the land use realities of alternative objectives and quantifying the tradeoffs associated with those [59]. Modelling can help to explore land use futures that navigate such tradeoffs by optimizing sets of objectives while minimizing tradeoffs [46,60,61]. Examples that move beyond exploratory scenario modelling include the work of Wolff et al. [62] that visualized how the world would look like if all agreed land restoration goals in international treaties were met, and Mehrabi et al. [63] who assess the consequences of conserving half of the land area for biodiversity conservation. While the individual goals of these studies are laudable, the resulting global land use patterns may not be considered the most desirable due to competing claims for space. Such studies help the translation of single goals to more consistent and synergetic land use futures and open the debate on what future land use we want. Verkerk et al. [64] sketch an alternative approach where stakeholder visions are matched with a large set of exploratory scenarios to identify the conditions and policies that would bring land use closer to stakeholder defined visions. This paper is an early implementation of the call of Rosa et al. [65] for visionary biodiversity scenarios. A more advanced implementation of this approach is presented by Cooper and Dearing [66] who model fishery systems to show under which conditions different pathways to safe and just socio-ecological systems are feasible.

Conclusion

Land use modelling can play multiple roles within land system science and has a critical role in major environmental assessments, both as a mechanism to evaluate drivers of global environmental change and as a means to mitigate or adapt to global change. While progress is made in refining existing models and in the field of participatory modelling, major aspects important in representing socio-ecological system dynamics are insufficiently addressed in existing models and many approaches do not use comprehensive model evaluation procedures to secure an understanding of uncertainty and a continuous learning process. While these challenges are mentioned before, progress towards resolving these is small. Land system modelling needs to move beyond incremental improvements towards testing new model structures and new workflows focused on cross-scale interactions, diversity in human agency and the links between demand and supply sites. This may lead to increased complexity of models which conflicts with calls for simpler models to support stakeholder engagement and inform policy making. However, lower complexity does not mean better science, and simplifications can lead to potentially incorrect conclusions if spill-overs and feedbacks are ignored. We thus argue that while higher complexity models may be more difficult to use in policy circles, such difficulty is clearly offset by their greater realism and rigor [37b]. Currently, many important aspects of land system science are only addressed by qualitative methods and ignored by large scale models used at the science-policy interface (i.e. IPCC and IPBES). Therefore, we call upon the scientific community for innovative modelling approaches that better embed our understanding of land systems, and on the lead scientists of major assessments such as IPCC and IPBES to move beyond the established set of IAMs and open up to insights obtained from new land system model types. This way, land system science could move beyond using models as assessment tools and towards the use of models as virtual laboratories to stimulate societal learning and the co-design of sustainability solutions.

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